Heavy Ion and Proton-Induced Single Event Multiple Upset

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Abstract

Individual ionizing heavy ion events are shown to cause two or more adjacent memory cells to change logic states in a high density CMOS SRAM. A majority of the upsets produced by normally incident heavy ions are due to single-particle events that causes a single cell to upset. However, for grazing angles a majority of the upsets produced by heavy-ion irradiation are due to single-particle events that cause two or more cells to change logic states.

Experimental evidence of a single proton-induced spallation reaction that causes two adjacent memory cells to change logic states is presented. Results from a dual volume Monte-Carlo simulation code for proton-induced single-event multiple upsets are within a factor of three of experimental data for protons at normal incidence and 70 degrees.

I. INTRODUCTION

Modern semiconductor transistor fabrication techniques have allowed manufacturers to place a large number of cells onto a small die area. This high cell density implies that separation distances between the sensitive regions of adjacent cells are small, the CMOS SRAM used in this study has separation distances near 4 μm [1]. Devices with small separation distances can have multiple sensitive junctions collecting charge that is liberated by a single particle interaction.

A multiple bit upset (MBU) is defined as any event or series of events that cause more than one bit to be upset during a single measurement. There are several classes of MBUs. One example is a single-word multiple bit upset (SMU) [2] which is defined as a single particle interaction that produces errors in more than one bit in a single word. In this work we define a single event multiple upset (SEMU) to occur when a single particle causes a series of physical adjacent cells to change their logic state. This can be heavy ion or proton induced.

The first reported observation of an MBU is given in [3]. Space hardware that encountered MBUs is described in Refs. [4,6] and references contained in [5]. The first step towards predicting of MBU rates is given in Ref. [7] where they developed the equations for the projected area that a unidirectional particle beam must cross for a given path length through two rectangular parallelepipeds. Smith *et al.* [8] simplified the equations and developed a rate prediction model that was shown to agree with flight data. Koga *et al* [2,9] reported that a CREME like code was developed at Aerospace Corporation that computes the expected rate for SMUs, one must assume that this code could also be used to predict SEMUs rates. The above techniques for computing rates for the class of MBUs where more than one sensitive junction must collect charge, i.e. SMU and SEMU, are valid as long as the rectangular parallelepiped model of the sensitive holds true.

A single normally incident heavy ion has been shown to cause SEMUs in SRAMS [10,11,12] and DRAMs [13,14,15, 16]. In all cases, it was concluded that the diffusion of charge to at least one junction was the cause of the SEMUs. As spacing is decreased between sensitive junctions one would expect that at some point the ion track diameter would be large enough to span the gap between the two junctions (Fig. 1), leading to prompt and possibly funnel charge as the dominate component of the collected charge. If the collected charge is large enough both cells would upset.

Simulation techniques that numerically solve the semiconductor device physics equations simultaneously have been employed to investigate SEMU for DRAMs [10,11,12] and for CMOS SRAMS [19]. The device geometry used to study SEMUs in the CMOS SRAM was comparable to the geometry of the device used in this study. Normally incident ion tracks were considered. In both cases it was determined that diffusion charge was the dominate component of the collected charge for at least one junction.

Figure 2 shows a heavy ion crossing through the sensitive regions of two adjacent cells at some grazing angle. Grazing or near grazing SEMUs have been observed in several devices [17,10,11,18,1]. These event types are assumed to be dominated by prompt and possibly funnel charge, while it is conceivable that diffusion charge could contribute significantly to the collected charge for angles of incidence between normal and grazing.

Ionizing heavy ions are not the only reactions that can cause two adjacent cells to change their logic state. Figure 3 shows a single proton-induced spallation reaction that has reaction products that pass through two sensitive regions. The range of such particles are less than a few micrometers and the LETs are below 15 MeV-cm^2/mg, therefore the separation distance must be on the order of a few micrometers and the

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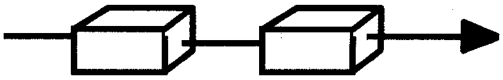

Figure 1. Cartoon of a grazing angle heavy ion crossing two sensitive regions of physical adjacent cells. Both memory cells would upset if there is sufficient charge deposited in the sensitive volumes.

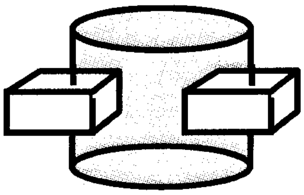

Figure 2. Cartoon of a normally incident heavy ion crossing two sensitive regions of physical adjacent cells. Logic changes would occur if threshold LET is exceeded.

circuitry must have a low critical charge for both cells to upset.

We will present results from dynamic tests carried out on a Matra's HM65656 CMOS SRAM showing that SEMUs occur for both proton and heavy-ion exposures. Reference [1] presents the results of an exhaustive study of heavy ion SEMUs for the HM65656. This paper presents SEMU data collected independently with different test hardware and at a different facility. The new heavy ion data presented here shows that SEMUs occur more frequently than single cell upsets for large angle irradiations at LETs greater than 25 MeV-cm^2/mg. This has serious implications on how ground testing should be carried out and space upset rates are determined.

We will also present the first comparison of proton-induced SEMU experimental data and results from a dual volume Monte-Carlo proton-induced spallation reaction simulation. The low cross section for proton-induced SEMUs indicates that for this device proton-induced SEUs, not SEMU, will dominate in a space environment.

As device cell density becomes greater one would expect that heavy-ion-induced and proton-induced SEMUs will become the important event both in space hardware and on ground based tests. Hardware configuations used to test these high density devices should have the ability to distiguish between single particle single upsets and single particle multiple upsets.

II. EXPERIMENTAL PROCEDURE

The device chosen for this study is a 32k x 8 CMOS SRAM manufactured by Matra MHS [1]. The die is approximately 8 mm long and is divided in eight sections, one section for each bit. The sections are a matrix of 128 columns by 256 rows, one element for each byte. The physical bit map was provided by Matra and verified using the laser facility at the Naval Research Laboratory. Matra also provided a cell layout diagram. Laser upset measurements agree with the cell layout [1].

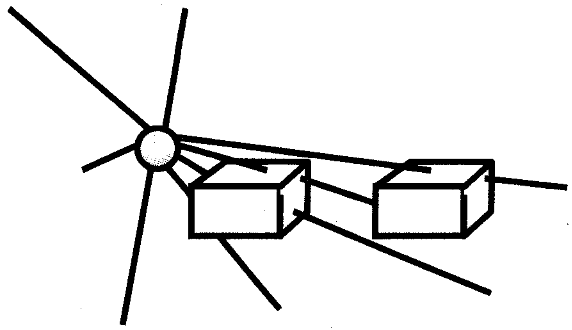

Figure 3. Cartoon of proton-induced spallation products crossing two sensitive regions of physical adjacent cells. If energy deposition in both volumes is larger that the critical amount, both cells would change logic states.

A block diagram of the test setup [20] is given in Fig. 4. The equipment enclosed in the dashed line is accessed by the remote host computer through an RS232 port. The slave accesses the DUT through a 40 pin ribbon cable. The slave loads a defined pattern into the DUT prior to irradiation. The beam is turned on. The slave interrogates the DUT until an erroneous byte is encountered. The slave then transmits the address, time stamp and the valid and invalid byte value back to the host. The erroneous bit is corrected and the slave continues to interrogate the DUT. The slave can complete a full evaluation of all 32k addresses in 0.5 seconds if no errors are encountered. The time for the host to record each error and return control to the slave is 0.023 seconds.

The requirements for an event to be named an SEMU are as follows.

- Less than 0.1 % of the memory cells are upset during a full scan of the memory.
- The time to complete a scan is 1 second or less.
- Low flux so that there is a low probability of more than one particle upsetting adjacent cells within the 1 second.
- Two or more adjacent cells are upset during a single scan.

The high-energy heavy-ion measurements were performed in air at the Tandem Accelerator Super-conducting Cyclotron (TASCC) facility at the Chalk River Laboratories of AECL Research, Canada. Table 1 shows the characteristics of each particle. The maximum flux used was $1x10^4 \pm 1x10^3$ p/cm^2/sec. The proton measurements were carried out at Crocker Nuclear Laboratory - UC Davis's cyclotron. Proton tuned energies were 12 and 63 MeV. The degraded proton energies were 24.5 and 37 MeV. The maximum flux used was $2x10^8 \pm 1x10^7$ p/cm^2/sec.

Table 1. High energy heavy ion particle beams used at TASCC.

ION	Br	F
E(GeV)	0.54	0.13
LET	33	3.5

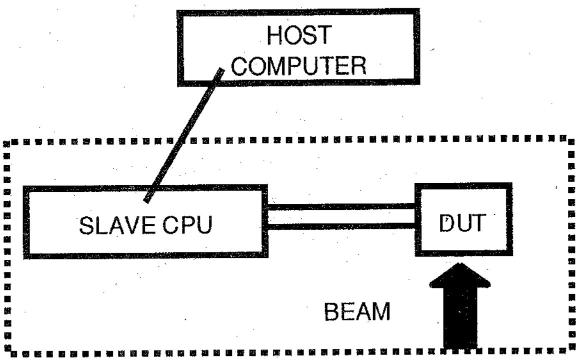

Figure 4. Block diagram of experimental setup.

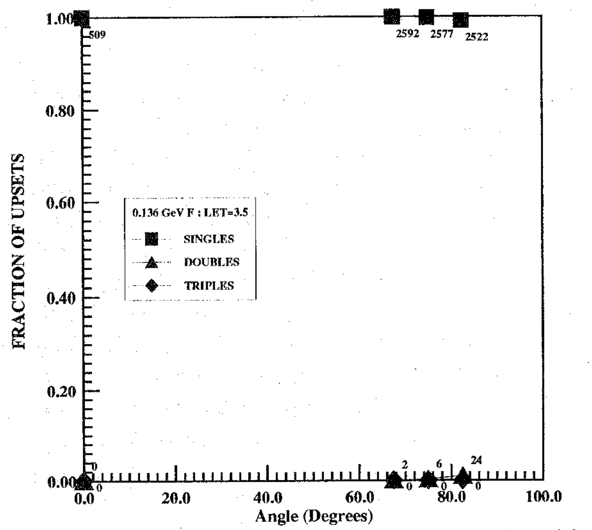

Figure 5. Fraction of upsets versus angle of incidence collected for the Fluorine beam. A small fraction of the upsets are due to SEMUs.

III. RESULTS AND DISCUSSION

A. *Results from Heavy Ion Exposures*

Samples of the heavy ion results are shown in Figs. 5 and 6. The plotts show fractions of upsets that are single memory upsets, double memory upsets and triple memory upsets versus the angle of incidence. For low LETs, as shown in Fig. 5, only about 1% of the upsets were doubles when the angle of incidence was very large. SEMUs were not observed at normal incidence. Figure 6 shows data for an LET of 25 MeV-cm^2/mg. SEMUs do occur at normal incidence for this LET. At grazing angles the fraction of the upsets due to doubles is greater than the fraction due to singles.

SEMUs dominate the SEU cross section when data is collected near grazing angles for LETs greater than 25 MeV-cm^2/mg. Grazing angle measurements are rarely taken and are even more rarely considered when computing single event upset rates expected in space. Memories with smaller separation distance between sensitive regions will exhibit angular effects that are more dramatic than the presented data. Also, as device geometries shrink ion-track structure effects may begin to dominate the charge-collection process.

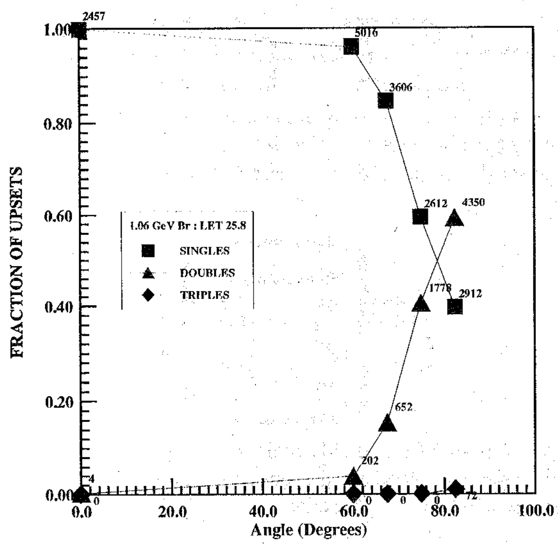

Figure 6. Fraction of upsets versus angle of incidence data collected using a high energy Bromine beam.

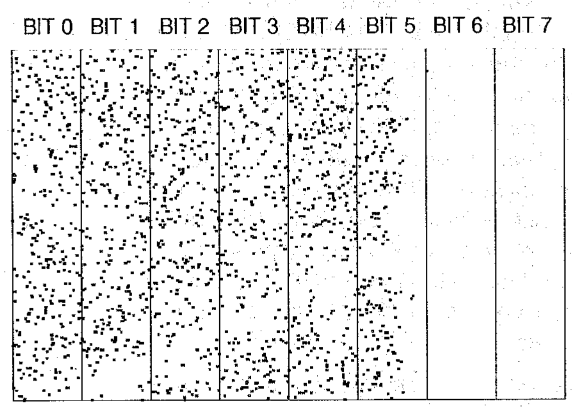

Figure 7. Physical mapping of all upsets observed for Bromine incident at 82.5 degrees. Shadowing from packaging and from wire mesh that supports the exit window are evident.

Figure 7 shows a physical mapping of the upsets across the die for 82.5 degree exposure to 1.06 GeV Bromine. Shadowing from the package occurred for a portion of bit 5 and all of bits 6 and 7. A track of bits were shadowed beginning at the lower right corner of bit 0 moving across the die towards the center of bit 5. Another track intersects the first track in bit 5 and crosses the die towards the center of bit 0. This is a characteristic of the beam that is impinging on the die. The test were carried out in air, see Fig. 8. The window was supported by a wire mesh. The shadowing is due to this mesh. Data collected at facilities with this beam configuration must be corrected when this type of shadowing occurs.

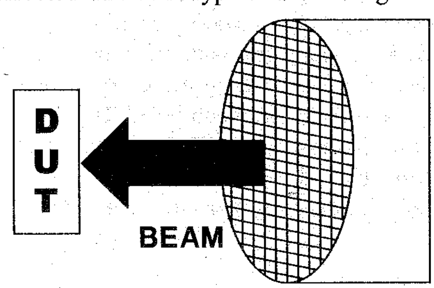

Figure 8. In air beam configuration.

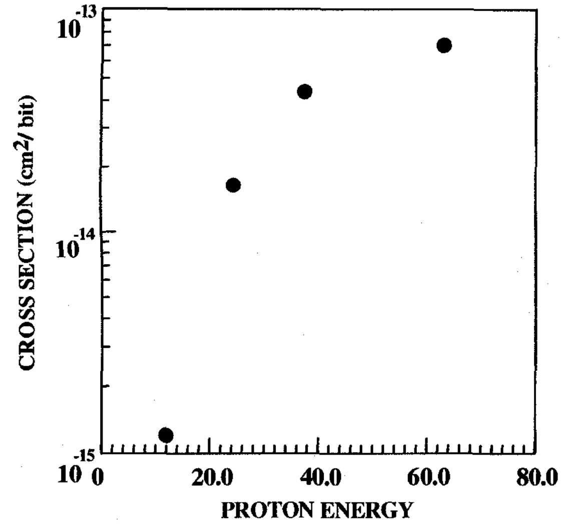

Figure 9. Experimental cross section measurement on the Matra 65656 SRAM for various proton energies in MeV.

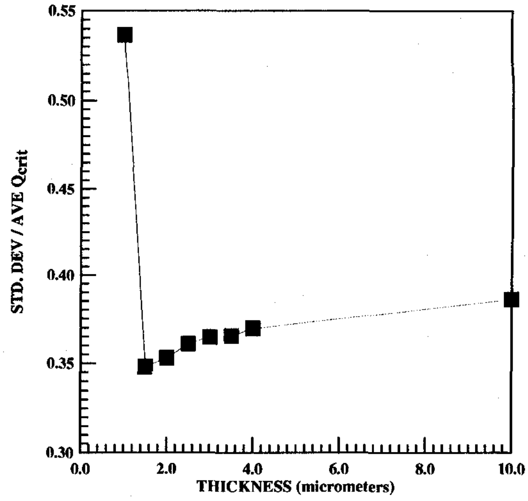

Figure 10. The thickness associated with minimum value of the standard deviation divided by the average value of the critical charge shows the estimate of the sensitive volume thickness.

B. *Results from Proton Irradiations*

Figure 9 shows the results from the proton exposures. It plots the SEU cross section versus the proton energy. One SEMU was observed at zero degrees for 63 MeV exposures. Two SEMUs were observed at seventy degrees for 63 MeV exposures. SEMUs were not observed at any other energy. This study represents one of the first reports of a ground based measurement that shows proton-induced SEMUs. The low cross section for observing a proton-induced SEMU in this device indicates that there is a very low probability of observing SEMUs in a space environment.

As device manufactures reduce geometry, SEMUs could be the dominating effect for both heavy ion and proton irradiations. Therefore, it is important to understand the physics of proton-induced SEMUs. The following is a summary of all known reports of spallation reaction-induced SEMUs. During the study discribed in Ref. [16] the authors observed proton-induced SEMU's [21]. Campbell *et al.* [22] reported that proton-induced multiple upsets were observed in space on CRRES. Smith [23] reported multiple upsets due to trapped protons for the 93L422. Recently, Label *et al.* [24] reported observing proton-induced SEMUs in a device manufactured by Hitachi during ground based and space measurements. Norman [25] tested the device used in this study for neutron-induce SEMUs, none were observed. They indicated that neutron induced SEMUs have been observed in other devices.

IV. SIMULATIONS

The CUPID [26] Monte-Carlo code simulates proton-induced spallation reactions. It determines the energy deposited in a rectangular parallelepiped by all of the spallation products. The results from the proton tests shown in Fig. 9 and predictions made by CUPID for various thicknesses at these energies determine the thicknesses of the sensitive volume and the critical charge [27]. The minimum in a plot, Fig. 10, of the standard deviation of the estimated critical charge for each energy normalized to the average value of the critical charge versus the thickness gives an estimate the thickness of the sensitive volume to be 1.8 μm and the average value of the critical charge for this thickness of 2.9 MeV (22.5pC=1MeV in Si).

COSMIC [28] is a modification of the code to include beams incident at various angles of incidence, including omnidirectional exposures. During this study, the COSMIC code was modified to include two volumes. The dual-volume code determines the cross section for depositing an energy E or greater in both of the volumes.

A separation distance between the sensitive structures of 4 μm was determined from the cell layout diagram provided by Matra. Simulations were carried out for 63 MeV protons. Figure 11 plots the integral cross section for depositing an energy E or greater in both of the volumes versus the energy deposited. The bottom curve is the result for normally incident protons and the top curve shows the result for an angle of incidence of 70 degrees. The vertical line indicates the value of the critical charge (2.9 MeV). The horizontal lines, one for each angle of incidence, indicate the expected value for the cross section for upsetting both cells. The predicted number of upsets is determined by the product of the cross section and the fluence used to collect the experimental data. Table 2 compares the prediction from the simulation code and the experimentally observed values. The fluence is the total fluence that the device was exposed to during the experimental investigations. The predictions are within a factor of three of the experiment. Experimental data collection was limited by total dose effects.

Table 2. Comparison of the experimentally observed proton induced SEMUs and the prediction using a modified version of the COSMIC code.

ANGLE	EXP	PRED.	FLUENCE
0	1	2.0±0.4	5.5E10 (cm^{-2})
70	2	5.3±0.6	2.8E10 (cm^{-2})

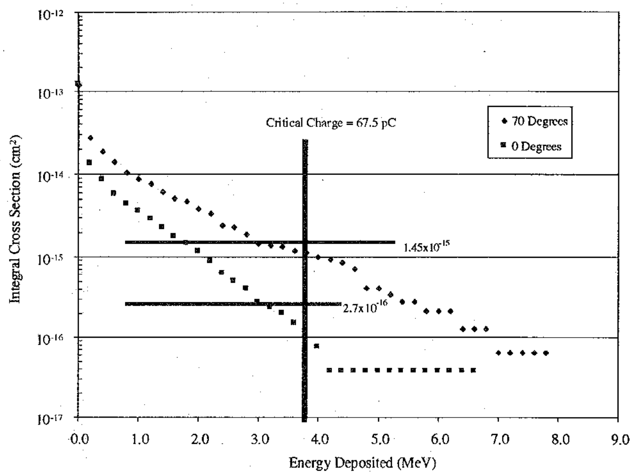

Figure 11. Dual-volume Monte-Carlo code results plotted as cross section for deposition an energy E or greater in both volumes versus the energy deposited. The bottom curve is zero degrees, while the top is an incident angle of 70 degrees.

V. CONCLUSIONS

Heavy-ion and proton measurements show single-event multiple upsets. SEMUs were observed for all angles of incidence for LETs greater than 25 MeV-cm^2/mg. More than half of the upsets at grazing angles were due to SEMUs. Low-LET heavy ions showed a small fraction of SEMUs only at large angles of incident. A very small number of proton-induced SEMUs were observed. Testing this device at higher proton energies is recommended. Predictions from a dual-volume COSMIC code are within a factor of three of observed proton-induced SEMUs.

VI. REFERENCES

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